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Before the
FEDERAL COMMUNICATIONS COMMISSION
Washington DC 20554

In the Matter of:

Proposed changes to the Amateur Service Rules (Part 97) to facilitate additional uses of certain portions of amateur spectrum by Amateur Spread Spectrum emitters	))))	RM-8737

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REPLY COMMENTS OF PHILIP R. KARN, JR, KA9Q IN FAVOR OF THE PROPOSAL

I make these comments in reply to those of the Southern California Repeater and Remote Base Association, The San Bernardino Microwave Society, The Mid-America Coordination Council, The SouthEastern Repeater Association, George Isley, the Wisconsin Association of Repeaters, and John Mock to the extent that they oppose the proposal to liberalize the amateur spread spectrum (SS) rules.

PERSONAL BACKGROUND

I have held an amateur license since 1971. I have been primarily interested in and have contributed to the technical advancement of amateur communications systems, including satellite and packet radio.

Of particular relevance to this proceeding is that since 1991 I have been a Staff Engineer at Qualcomm Incorporated in San Diego, California. At Qualcomm I participate in the design, development and testing of an advanced Code Division Multiple Access (CDMA) spread spectrum system for digital cellular telephony that is now being deployed commercially worldwide. My work with this technology has been an invaluable educational experience with useful insights into the potential benefits and drawbacks of SS in the amateur service.

I write these comments on my own personal initiative as a radio amateur, not on behalf of Qualcomm. Qualcomm is in the commercial cellular telephone business, not the amateur radio equipment business. As far as I know, Qualcomm has no corporate position on this matter.

GENERAL COMMENTS

I strongly support the liberalization of the spread spectrum rules as proposed by the ARRL. I believe this technology has much to offer the amateur service. The potential direct benefits include substantial increases in the efficiency and quality of existing services (e.g, mobile voice communications) as well as enabling qualitatively new applications such as very high speed packet radio.

The indirect benefits would be even greater. Spread spectrum is now an important commercial radio technology, thanks to innovations such as the Global Positioning System (GPS), Part 15 wireless LANs and CDMA cellular telephones. It is essential that radio amateurs develop a hands-on understanding of SS technology not just to improve their communications abilities, but also to continue to satisfy the basis and purpose of the amateur service relating to technical experimentation, advancement and training as stated in Sections 97.1(b), (c) and (d).

So I am considerably distressed by the negative comments received so far in this action. They exhibit a remarkable degree of ignorance of the principles of spread spectrum and of basic communications theory, a strong fear of the unknown, and an unreasonable desire to maintain the status quo at all costs in a rapidly changing world.

DEFINITION OF "SPREAD SPECTRUM"

In my comments I will use the term "spread spectrum" in a relatively expansive sense. The usual definition includes

- Pseudorandom frequency hopping (FH) of a conventional narrowband signal
- Pseudorandom direct sequence (DS) spreading of a conventional narrowband signal
- Miscellaneous spreading techniques: time hopping, etc.

To this list I add

- Forward error control coding (FEC)
- Nonbinary modulation with large orthogonal signal sets, e.g., M-ary FSK where M >> 2 (many more than 2 tones)
- Wideband analog FM

FEC, nonbinary orthogonal modulation and wideband analog FM all resemble FH and DS in that they increase emission bandwidth beyond that occupied by an uncoded binary (or SSB-AM) signal at the same user data rate. The power spectral density is also decreased. But while FH and DS are usually "power neutral" -- the same transmitter power is generally required whether or not the signal is spread [1] -- FEC, nonbinary orthogonal modulation and wideband analog FM can all have the extremely desirable property of *decreasing* the total RF power required to support a given user data rate or audio S/N ratio. This necessarily comes at the expense of increased bandwidth, according to Shannon's famous formula that shows channel capacity to increase with both signal power and bandwidth.

I use this expanded definition of SS because the Commission's existing emission bandwidth limits keep amateurs from not only using spread spectrum as it is generally defined, but also from using wider bandwidths to reduce RF power requirements.

BENEFITS OF POWER-EFFICIENT SS

This fundamental tradeoff between bandwidth and power was established by Shannon in his famous 1948 paper *A Mathematical Theory of Communication*, but its implications have not been well appreciated in amateur practice. An early voice in the wilderness was that of John Costas, K2EN, who published the paper *Poisson, Shannon and the Radio Amateur* in the Proceedings of the IRE in December 1959. Costas argued eloquently and passionately that the chaotic and congested amateur bands were ripe for wideband techniques. The notion that wider bandwidths can actually increase spectral efficiency is a seeming paradox that many find hard to accept. This was evidently true for Costas' contemporaries:

> The frequency diversity [SS] system is intuitively ridiculous because it apparently "wastes" bandwidth rather indiscriminately. As we shall see, intuition is a poor guide in these matters. The feeling that we should always try to "conserve bandwidth" is no doubt caused by an

environment in which it has been standard practice to share the RF spectrum on a frequency basis. Our emotions do not alter the fact that bandwidth is but one dimension of a multidimensional situation.

The other dimensions to which Costas alludes include time (e.g., duty cycle), RF power and geographical area. In particular, the amateur service has all but ignored the RF power dimension, giving little more than lip service to the requirement to run only the minimum power required to maintain communications. The FCC rules are also at fault to the extent that the bandwidth limits established for various band segments preclude the use of power-efficient wideband techniques.

It's sad to consider while reading many of the comments filed in opposition to this proposal that Costas wrote this paragraph over 36 years ago. Here are some typical "NIMBY" (not in my back yard) comments:

> There are less crowded Amateur microwave bands, particularly the higher frequency bands, where space exists for a variety of SS emission types. [San Bernadino Microwave Society, at 9.]

> The petitioner's pro-SS arguments in this matter only address technical and experimental concerns, and do not seriously consider the ill effects of the co-spectrum use of SS and existing narrowband systems in an already crowded spectrum. [SouthEastern Repeater Association at 3]

Such comments betray a complete ignorance of the potential of spread spectrum to substantially *decrease* congestion. Other comments, while grudgingly admitting some potential for improvement, misunderstand and deprecate the technology:

> It is a fact that a digitally processed SS system utilizing "exclusive" spectrum can accommodate more traffic in the same bandwidth than can a FDMA system. This is mostly a result of the digital processing to compress (in time) the communications and the use of all the available spectrum space without having to leave "guardbands" between each user assignment. It is also dependent upon the communications user being willing to tolerate propagation delays which will increase as the system traffic increases. [Comments of SCRRBA at 6]. [2]

Costas shows that what a wideband system "spends" in excess bandwidth can be more than repaid by vastly increased interference resistance and by significantly reduced RF power requirements (meaning less interference to existing narrowband users.) Even with the limited analog technology of his day, Costas could show a net increase in the carrying capacity of a given frequency band. Subsequent developments in digital signal processing technology and error correcting codes have now made it possible for one commercially practical spread spectrum system (Qualcomm CDMA) to demonstrate, in carefully controlled field tests, capacity gains of 10-15x over existing narrowband analog FM cellular systems. Such dramatic gains are only possible in a wideband system. They are clearly of greatest value in our most congested bands!

A simple thought experiment will show how reducing power is the key to spectrum efficiency, and that limiting bandwidth is actually counterproductive. Assume a 1MHz band saturated with 1000 uniformly distributed users who, because shortsighted FCC rules preclude power efficient wideband modes, must run 1KW each to maintain communications with some narrowband scheme. The total transmitted power spectral density in the band is therefore 1000x1KW/1MHz = 1 watt/Hz. This represents the spectral density of interference as seen by a new user just arriving on the band.

Now assume that the rules are changed by an enlightened Commission to allow a power efficient wideband scheme that requires only 500W, spread over all or some random part of the 1 MHz band, to maintain communications against 1 watt/Hz of interference spectral density. If a few users switch to this mode, the overall interference level will go down by a small but nonzero amount. An individual narrowband user may see either an improvement or a degradation, depending on how close it is to a wideband station. [3]

But let's say the new mode really catches on, and all 1000 stations switch over to it. Now the interference spectral density is only 1000x500W/1MHz = .5 watt/Hz. Since the interference has gone down by 3dB, each station can now lower its power accordingly, to 250 watts. This lowers the total interference again, to .25 watt/Hz, and the stations can all reduce their powers again by another 3dB. And so on.

If interference from other stations were the only factor, this power "deescalation" could continue indefinitely until everyone ran virtually no power at all! Of course, at some point in a real system natural noise sources will emerge to stop the process.

Alternatively, let's keep our original 1000 wideband transmitters at 500W and add a second batch of 1000, each also operating at 500W. This would produce an interference spectral density of 2000*500/1MHz = 1W/Hz, which we know is the most our wideband scheme can tolerate at 500W. Now we have twice as many users sharing the band as in the narrowband case. All this because we removed the rules against "wasting" bandwidth!

The message is clear: if our objective is to promote spectral efficiency, *limit power -- not bandwidth.* The proposed rules achieve this by requiring automatic power control in exchange for decontrolling bandwidth. Having seen the inverse relationship between S/N ratio and band capacity, we can also understand the proposed limit on Eb/N0 ("digital S/N"). Since each decrease of 3dB in required Eb/N0 doubles the capacity of a shared band, amateurs should be encouraged to build and operate systems at the lowest possible Eb/N0 ratio. Because of the relatively generous 100W power limit, and because there is no limit on data rate, the Eb/N0 limit effectively says "take all you want, but eat all you take." Since the theoretical limit according to Shannon is -1.6 dB for infinite bandwidth, there is clearly a lot of room for improvement here.

WEAK SIGNAL AND SATELLITE INTERESTS CAN BENEFIT FROM SS

Some of the most vociferous opposition to SS comes from the weak signal operators. I believe this is because they fail to understand that they have as much to gain as anyone from the relaxation of emission bandwidth limits. Many weak signal DXers long ago reached the limits of what can be accomplished by brute force; they erect the largest antennas they possibly can, they build the lowest noise amplifiers possible, and they run the full legal power limit. ("Moonbounce" operation is perhaps the best example.) Yet these operations are severely hampered by a "narrowband" mindset. Digital modulation and coding techniques that spend bandwidth to gain power could be of enormous benefit to these operations. Indeed, they represent an argument for not limiting wideband emissions to 100W when higher powers are truly necessary and interference to other operations can be controlled. (Again, moonbounce is a leading candidate here.)

Amateur satellite operation can also benefit substantially from wideband techniques. Power is a limited commodity even on expensive commercial satellites; on amateur satellites it is extremely scarce. The carrying capacity of these satellites could be increased considerably through the use of power-efficient wideband modulation and coding techniques. Furthermore, auxiliary applications of spread spectrum such as highly accurate tracking of spacecraft are clearly of considerable benefit.

One of the nice aspects of spread spectrum operation by satellite is that the near-far problem is often nonexistent. A satellite in high orbit is nearly equidistant from its users, so the range of user signal strengths it sees is scarcely affected by varying propagation losses.

I point out here that the amateur rules should *not* require any minimum processing gain or spreading bandwidths. Particularly in the relatively narrow weak signal band segments where the use of wideband techniques is more likely motivated by RF power savings than by minimizing power spectral density, requiring more bandwidth than necessary to achieve the desired power gains would be counterproductive. Any such standards should be promulgated by voluntary agreement among the users of each band segment.

INTERFERENCE CONCERNS

The main concern expressed by the comments in opposition involve the potential interference from SS systems to existing narrowband operations.

To the extent that any of the comments contain actual numerical analyses, all are based on absolute-worst-case conditions. (See, for example, SCRRBA's comments at 5). They assume continuous use by the SS station of the maximum power of 100W, completely discounting the mitigating effects of duty cycle and automatic power control. They assume reckless and total disregard on the part of the SS operator for voluntary bandplans and interference complaints from nearby narrowband operations. Then they argue that because interference *could* occur under such extreme conditions, SS ought to be banned entirely or at most permitted under extremely restrictive rules.

Yet with such unreasonable assumptions, *any* operating mode could cause harmful interference. Indeed, most would be even worse! For example, it is legal under current rules to operate local FM simplex at 1.5KW on a satellite downlink band. (Never mind that such power levels are extremely rare. Those who oppose SS ignore my protests that average power levels will be substantially less than 100W, so I am entitled to make equally unreasonable assumptions here).

The average transmitted power spectral density of such a signal would be 1500W/20 KHz = 75 milliwatts/Hz, with many strong discrete spectral components. In contrast, a 100W SS signal spread over 1 MHz would be only 0.1 milliwatt/Hz. Whatever can be said about the interference potential of the latter signal is clearly even more applicable to the former. Yet FM is not banned from the satellite bands. Indeed, had such a ban been enacted it would have precluded the use of FM by satellites such as the Microsats.

The potential for interference is a fact of life in amateur radio. The FCC has long charged amateurs with the primary responsibility to work things out for themselves:

> Each station licensee and each control operator must cooperate in selecting transmitting channels and in making the most effective use of the amateur service frequencies. No frequency will be assigned for the exclusive use of any station. [FCC Rules Part 97.101(b)]

This rule would apply to SS operations with equal force. It is patently unfair to insist that "no SS interference potential whatsoever is tolerable" when no other mode is held to such an unattainable standard.

Although some, such as the Southeastern Repeater Association, raise the issue of interference to emergency communications, I consider this a red herring. This argument no longer carries much weight given the popularity of cellular telephones. [4] The nominal purpose of the amateur service is technical experimentation and self-training; it not a "safety of life" service like aeronautical or police radio where even occasional interference really cannot be tolerated.

But I do agree with the San Bernardino Microwave Society when they say that SS operations should adhere to local frequency coordination practices, assuming that these practices make reasonable accommodation for SS operations. For example, it would indeed be inappropriate to run a high speed SS metropolitan computer network in a band segment reserved for weak-signal DX. But this is an issue best handled by the voluntary bandplanning process, not the slow and inflexible FCC rulemaking process.

I further believe that the voluntary bandplanning process should isolate operation "classes" *without* regard to modulation mode or bandwidth. For example, a band plan might specify the following subbands:

- Terrestrial weak-signal operations
- Satellite operations
- Local "utility" operations, further divided into
    - Low-altitude transmitters (e.g., repeater outputs)
    - High-altitude transmitters
    - Remote receivers (e.g., repeater inputs)
    - Low-altitude simplex

Any modulation mode would be permitted in any subband as long as the operation is consistent with the subband class and any voluntary agreements promulgated by the users of that class. For example, one could use power-efficient SS-like techniques such as forward error correction coding in the weak-signal segment to work DX, but not to run a local area network. Similarly, spread spectrum would be allowed in the satellite segment if the purpose is to communicate through a satellite in accordance with good satellite practice.

Such band plans should completely alleviate the interference concerns of the weak signal and satellite groups while retaining the option to apply wideband techniques to their own needs as they see fit.

FM, packet and SS operations would coexist in the "local" subbands. One segment might be shared by FM, packet and SS repeater transmitters on hilltops while another would be shared by the receivers in these repeaters.

I note that current amateur band plans already look very much like what I have proposed here. This is not a coincidence! They have evolved in this manner to deal with the same "near-far" interference problem that is the source of so much concern with SS. That's because the near-far problem is not unique to SS, but exists to some degree with *every* operating mode because of the inability to build real receivers with perfect adjacent channel rejection.

The "MINIMUM POWER WINS" APPROACH TO INTERFERENCE RESOLUTION

Such band plans should nearly eliminate interference between stations using different segments. Within a given segment, however, interference may still occur. Again, such problems are best handled within the amateur service whenever possible. The FCC should only state general principles for resolving interference problems as opposed to laying down blanket prohibitions that more often than not cause spectrum to go idle altogether.

I note that in many such interference incidents, one or more parties are running excessive power. This suggests the following principle:

Whenever harmful interference occurs between operations otherwise in accordance with voluntary bandplans that cannot be resolved by mutual agreement of the parties involved, the primary responsibility for resolving the interference shall rest with the station running the greater RF output power, without regard to emission bandwidth.

This elegant rule clearly encourages power efficiency, which we have seen is directly related to spectrum efficiency. Being "interference driven", it avoids arbitrary and inflexible restrictions that would apply even when no interference would otherwise be caused.

One's mind almost boggles at the thought of two warring repeater groups in a power *de-escalation* battle in order to claim priority on a channel! Beyond that, this principle would certainly encourage the use of power efficient modes, directional antennas, low power relays, and of course the minimum power actually required in each instance to maintain communications.

Summary of Points

- I strongly support the ARRL proposal to liberalize SS emission types. Relaxing the bandwidth limits on amateur emissions is basic to the development of more power and spectrally efficient techniques of benefit to virtually *all* types of amateur operation, including local utility, DX and satellite;

- This can be best implemented not as a specific authorization for SS per se, but as a waiver of existing emission bandwith limits on "unspecified digital codes" that may be automatically obtained by adhering to the maximum power limits and automatic power control requirements discussed herein;

- SS should be allowed on as many amateur bands as possible, subject to the maximum power output limit and the requirement for automatic power control to limit receiver Eb/N0 ratios;

- There should be no rule mandating a minimum processing gain;

- Amateur SS operations should be encouraged to adhere to voluntary band plans;

- Band planners should be encouraged to make reasonable accommodation for SS by discriminating on the "class" of operation (e.g., local utility, terrestrial DX, satellite), not by emission bandwidth;

- Interference within each class of operation should be resolved by the "minimum power wins" principle. I encourage the Commission to adopt rules to liberalize the use of amateur spread spectrum, consistent with these points, as soon as possible.

Certification

I certify that I have made copies of these Reply Comments available to the commenters mentioned in the introduction by US mail, electronic mail and World Wide Web.

Respectfully submitted,

Philip R. Karn, Jr., KA9Q

Phil R. Karn

Footnotes

[1] Ideal implementations of FH and DS are "power neutral" on simple nonfading channels. Spreading can achieve power gains over fading channels thanks to the ability to separate multipath components separated by one or more chips and to add them constructively, e.g., in a "rake" receiver. These gains are limited to fading channels while FEC coding gains also exist on nonfading channels.

[2] Efficient SS systems need not "compress in time". Indeed, if that's all they did, there would be no net gain in capacity. They do compress the source material to remove redundancy, e.g., through the use of low-bit-rate speech encoders. Propagation delay is fixed; it does not increase with load (though the bit error rate will as the channel approaches capacity). And while SS does eliminate the need for inter-channel guard bands, this is generally not a major issue. The big capacity gains in an efficient spread spectrum system like Qualcomm CDMA come from the following:

- The ability to reuse the same spectrum many times in a geographical area without "exclusion zones" around each transmitter on a given channel to protect it from co-channel interference. A typical FM analog cellular system uses a 1:7 frequency reuse pattern, i.e., each cell can only use 1/7 of the total channel set lest it interfere with its neighbors. Because of its inherently strong resistance to co-channel interference, a CDMA system can reuse the same channel in *every* cell.

- The ability to exploit rapidly varying user demands (e.g., talk spurts) to reduce, through increased trunking efficiencies, the average total resources needed by a group of users sharing a CDMA channel. For a typical voice conversation, this yields a 60% reduction in average data rate. FDMA and TDMA systems could, in theory, reallocate frequency channels or time slots in an equally dynamic fashion. They generally do not do so because the considerable overhead required would squander any savings.

- The ability to deal with fading through a combination of rapid transmitter power control and "rake" receivers that isolate and recombine multipath components in a constructive fashion. This permits reliable mobile operation with virtually no link margin (approx 1 dB). This is contrasted with the substantial link margins commonly required in narrowband systems: analog FM cellular is typically engineered for a worst-case signal-to-interference ratio of 17 dB, 7 dB above the FM threshold. On amateur FM repeaters where user densities are much lower and automatic power control is nonexistent, far higher (and extraordinarily wasteful) link margins are common.

● The ability to operate on both fading and nonfading channels with less average transmitter power thanks to the use of strong error correction and interleaving. Field tests of Qualcomm CDMA resulted in an average reverse link (mobile-to-cell) transmitter power of only 1-10 milliwatts in a mixed urban/suburban environment, far less than the 300mW-3W common with FM in the same environment.

[3]This is the classic "near-far" problem; strictly speaking my analysis is valid only when every station is equidistant from all other stations. But later I will discuss practical band-planning approaches that minimize the near-far problem by segregating transmitters and receivers.

[4]On several occasions I have used amateur FM repeaters to report emergencies. About a month ago I encountered a seriously injured woman lying in the street after her car was hit by a drunk driver. I immediately called for help on a local 2m repeater. Eventually, I obtained police assistance with the help of an inexperienced albeit well-intentioned fellow ham who called 911 on his home phone. I later learned that the woman was expected to make a full recovery. But I was so frustrated by the inefficiency and undependability of the whole process that I finally bought a portable cell phone that I now carry with me at all times.